Modelling of Sub-micrometer Particle Concentrations in Free-flowing Freeway Traffic, Brisbane Australia: Some Empirical Results.

Fraser McGregor, Luis Ferreira and Lidia Morawska.

Physical Infrastructure Centre, Queensland University of Technology, 2 George Street, Brisbane, QLD 4000 Australia

Abstract

As road networks become increasingly more congested, environmental concerns relating to emissions from motor vehicles assume a higher significance. This study found that road side concentrations of particles produced by freeway traffic in Brisbane, Australia, is primarily dependent upon of traffic flow differentiated into fuel type, and wind speed. The analysis differentiates between diesel and petrol vehicles, and finds that particle concentration is very sensitive to the proportion of diesel fuelled vehicles. A 20% increase in diesel vehicles can produce an 18% increase in particle concentrations compared with a 2% particle increase for the same number of additional petrol vehicles.

Keywords Particles, sub-micrometer, particulate matter, traffic flows, modelling diesel fuel.

1.0 Introduction

In addition to pollutant gasses such as oxides of carbon and nitrogen, attention is now increasingly focusing on the sub-micrometer particle emissions resulting from the combustion processes of the transport fleet. Fine particles are less than 2.5 micron diameter ($PM_{2.5}$) and sub-micrometer particles are less than 1 micron diameter. However, for the purposes of this paper, the sub-micrometer particles considered are in the range of 0.017 to 0.890 micrometers, due to the constraints of the measuring equipment.

According to the United States Environmental Protection Agency (1997) a number of studies have linked particle matter, especially sub-micrometer particles with a series of significant health problems. In Australia alone, according to the University of New England (1999) inhaling particle matter is estimated to account for some 900 premature deaths per year.

The number of particles emitted at any site is dependent on variables such as the number and type of vehicles, the fuel used and the driving cycles. However, the concentration of particles found at a specific site is not only dependant on tailpipe emissions, but also the rate of dispersion of particles into the environment after emission. Furthermore, meteorological conditions such as wind speed, temperature, humidity and precipitation may have differing contributions to the final concentration.

Accurate determination of the tailpipe emissions for the entire vehicle fleet is impossible, as vehicles of the same model and age emit differently, depending on fuel, driving cycle, driver behaviour, vehicle tuning and other variables. For instance, Ullman et al. (1984) found that maladjustment of diesel engines could cause a 240%

increase in diesel particles. The Australian Academy of Technological Sciences and Engineering (1997) found that higher sulphur content diesel fuel produces higher number of particles. Therefore, while it can be satisfactory for strategic transport models to use Vehicle Kilometre Travelled (VKT) methods and fuel consumption figures to calculate gaseous emissions, as used by Pekol (1998). However, according to CONCAWE (1997) the same level of success has not been readily forthcoming for predicting particle emissions, according to. (CONCAWE originally meant CONservation of Clean Air and Water in Europe, and is the oil companies' European organisation for environment, health and safety.)

This study approaches the estimation of concentrations from an on-road measurement perspective. The actual measurements of particle concentrations were recorded over several months at five-minute intervals, along with details of the vehicle fleet at a site on an urban freeway in Brisbane Australia.

Other data, described below, was also recorded. From an analysis of this data, a model has been developed to predict the concentrations that could be expected at this type of site. The model has been then verified against the concentration data collected at this site.

This paper specifically investigates the relationship between the independent variables of vehicle flows by fuel type, and wind speed, against the dependent variable of particle concentration. This has resulted in a model that is relatively cheap to set up and run, as it relies on using data such as traffic flow and meteorological data which may well be already collected by local or government authorities for other purposes.

2.0 Data Collection at the site

The data collected relates to a section of the South-East freeway located approximately 10 km to the south of the Brisbane Central Business District (CBD). This is a straight section of divided motorway with two lanes in each direction with a slight uphill gradient (approximately 1%) to the north-west. Weekday peak hour flows are approximately 7,500 vehicles per hour at a speed of 100 km/h for uncongested conditions.

The motorway at this point passes through a cut with the Tora Street bridge crossing above the motorway providing access to a residential area. The walls of the cut slope at a 1:8 grade, with the top of the cut being approximately 5 metres high and 38m wide. As such, it could be considered to similar to a wide street canyon with low walls. The road is a major link between Brisbane and the Gold Coast to the south, as well as part of the interstate highway to the South.

The Queensland Department of Main Roads (DMR) maintains a permanent traffic counter at this site. This data was available to the study, giving total unclassified vehicle counts in each direction, in five minute blocks, for 24 hours a day.

In addition, video film was taken of the traffic flow in each direction over a period of three weekdays and one Saturday. This data was later used to classify the vehicles according to various criteria such as age, fuel type and vehicle type. However, this paper only considers weekday data, as vehicle flow at a given time is significantly different for weekend traffic.

Equipment recording the particle concentrations was installed on the bridge above the centre of the motorway. Particle characteristics were measured continuously at the site over a three month period. Sampled air was taken from a height of 3 metres above the middle of the median strip, with the selection of the sampling point based on satisfactory air mixing above the road, as discussed by Jamriska and Morawska (2001).

A scanning mobility particle sizer (SMPS) was used to measure particle concentrations and size distribution. The SMPS consists of an electrostatic classifier (EC) and a condensation particle counter (CPC). The sampled air is introduced into the EC where particles are size classified according to their electrical mobility and then counted in the CPC. Both instruments were set to operate in the particle size range of 0.017-0.890 micrometers with one measurement completed over a five minute interval. The sampled air was delivered to the instruments through a conductive sampling tube, with the counts being corrected for sampling tube losses. The concentrations are then given as particles per cm^3. (Jamriska and Morawska 2001).

The total particle concentration included particles from traffic as well as other background sources. An estimation of the level of background particle counts was obtained from a second SMPS located at an Air Monitoring and Research Station (AMRS). The AMRS has been monitoring gaseous and particle concentrations since 1995 on a continuous basis. This site is located approximately 200m from the same freeway, but 10 km to the north, on the top of a six-storey building. The data obtained from the AMRS was corrected to remove particle counts from the freeway by only using those counts that relate to wind direction that were not from the freeway direction. This data indicated a moving average background count of approximately 6000 particles per cm^3 Although it would have been ideal to have the background reading taken close to the freeway, duplication of the equipment to provide these readings was not possible within the scope of this study.

Instruments installed on the bridge also recorded the wind speed and direction at a height of 2.5m above the bridge. The Bureau of Meteorology (BoM) was able to provide ancillary data relating to temperature and humidity profiles for the data collection period.

3.0 Data Analysis

3.1 Vehicle Related Data

In order to analyse vehicles and particle counts within the same time frame, vehicle data was collected over the same five-minute time interval that particle concentrations were collected. Raw unclassified vehicle data was collected in separate northbound and southbound streams by the DMR.

Additional data to that provided by the DMR was needed to categorise the vehicle fleet into fuel and vehicle types, This was obtained by videoing the traffic flow in both directions during daylight hours for 3 weekdays and one Saturday during the data collection period, a total of 30 hours. There are 133 data points for the weekday analysis. For this study, the weekend data is excluded, as this has a different traffic profile in relation to vehicle flows and classification.

The video data was compiled into classified vehicle counts (i.e. vehicles per five-minute period) corresponding to the same particle concentration recording periods. The classifications used are found in Table 1. These classifications were identified by fuel type, and then aggregated into fuel type categories.

Table1
Classification of vehicles from video data

Classification	**Description**	**Predominant Fuel Type**
Large Cars	Large sedans, 6 cylinder	Petrol
Medium Cars	Medium Sedans, large 4 cylinder	Petrol
Compact Cars	Small cars up to approx 1.6l	Petrol
Station Wagons	Generally large cars with enlarged luggage area	Petrol
Private Vans	People movers e.g. Toyota Tarago, Camper Vans	Petrol
4WD	Vehicles capable of off road performance	Petrol/Diesel
LCV	Light commercial vehicles, vans. Etc	Petrol/Diesel
Light Truck	Two axle rigid body vehicles	Diesel
Heavy Truck	Three axle rigid and articulated vehicles	Diesel
Bus	School, public transport, tour coaches	Diesel
Taxi	Generally 6 cylinder vehicle, for hire	Petrol/LPG
Motorcycle	Two Wheel	Petrol

Previous studies by Australian Academy of Technological Sciences and Engineering (1997), Parsons (1988) and Morawska et al. (1998) have clearly demonstrated that the type and number of particles produced from vehicles also depends on the fuel used. Therefore, each classification was also identified by fuel usage, which was compared against the Australian Bureau of Statistics (ABS) vehicle registration data for aggregation. Aggregation is necessary as fuel type rather than vehicle classification is more of a determinant of emission characteristics. Furthermore, the resolution of vehicles into more detailed classifications is limited by the accuracy of the video analysis.

The Australian Bureau of Statistics (1999)contains data about the fleet composition and fuel type. This was used to provide an estimate of the numbers of different fuel types per category, i.e. cars and commercial vehicles (CV's), that could be expected to be found on the motorway.

As shown in Table 2, ABS data indicates that 2% of passenger vehicles are diesel fuelled. 4WD vehicles are also included among the passenger vehicles. Therefore, in determining the proportion of diesel vehicles from the video data, all passenger vehicles, including 4WD, are aggregated, and then split into petrol and diesel numbers. Passenger vehicles make up 75.2% of the vehicle fleet as shown in Table 3.

Table 2
Percentage Classification of Queensland Vehicles by Fuel Type (%)

1999 Registrations	Total Petrol(%)	Diesel (%)	Dual Fuel (%)
Passenger Vehicles	96	2	2
Campervans	66	30	4
LCV	73	23	4
Rigid <4.5 tonne	30	68	2
Rigid >4.5 tonne	18	81	1
Articulated	4	96	0
Non Freight Carrying	45	51	4
Buses	22	76	2
Motorcycles	100	0	0

Source ABS(1999)

Table 3
Percentage Classification of Queensland Vehicles by Category (%)

1999 Registrations	Fleet %
Passenger Vehicles	75.2
Campervans	0.2
LCV	17.1
Rigid <4.5 tonne	0.7
Rigid >4.5 tonne	2.3
Articulated	0.6
Freight Carrying	0.1
Buses	0.6
Motorcycles	3.2

Source ABS(1999)

The Australian Bureau of Statistics (1999) show light commercial vehicles (LCVs) as 77% petrol and 23% diesel. The video data was disaggregated according to these percentages. All trucks and buses in this study are considered to be diesel fuelled, based on the video data. The vehicle fleet fuel classifications were aggregated into petrol and diesel, with 2% passenger vehicle and 27% LCV being assigned to the diesel category. All trucks and buses were deemed to be diesel fuelled.

Vehicle flows for both the DMR and Video data were recorded in five minute intervals. These have then been converted to vehicles per hour (veh/h) and smoothed by using a simple moving average of each three adjacent data points as is usual for time series data, according to Chatfield (1975). From this data, peak hour flows were observed in the morning (7 to 8 am) and afternoon (5 to 6 pm). However, the proportion of diesel to petrol vehicles is not constant throughout the day, as the increase in traffic during peak hours is mainly due to commuter passenger vehicles, as can be seen in Figure 1.

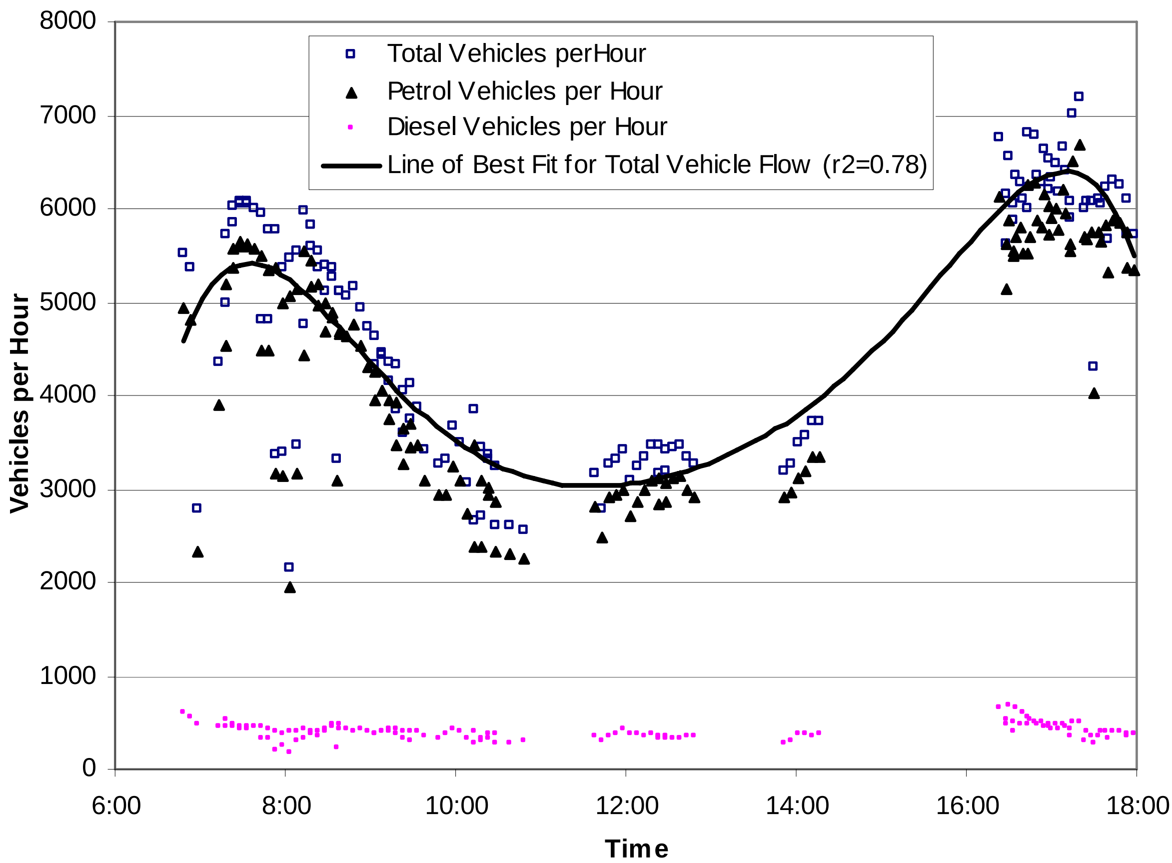

Figure 1. Moving average weekday vehicle flow by fuel type from video data

Analysis of the above data revealed that for vehicle flows from 1,500 to 7,500 veh/h there is a close correlation (r^2 =0.998) between petrol vehicles and total vehicles as shown in Figure 1. It was possible to calculate the expected diesel proportion for any total flow rate observed between these values for the daytime period. The regression equation (n=131, r^2=0.997) for calculating the number of petrol vehicles is given by:

$$\text{Petrol Vehicles} = 0.9561 \times \text{Total Vehicles} - 190.14 \qquad \text{(Eqn 1)}$$

The number of diesel vehicles for the same flow rate is then taken as the total flow less the petrol vehicle flow.

This equation allows the non-classified DMR counts that covered a period of several months to be split into petrol and diesel fuels for the daytime periods and for flow rates of 1,500 to 7,500 veh/h so that the larger DMR data set can be analysed by fuel type.

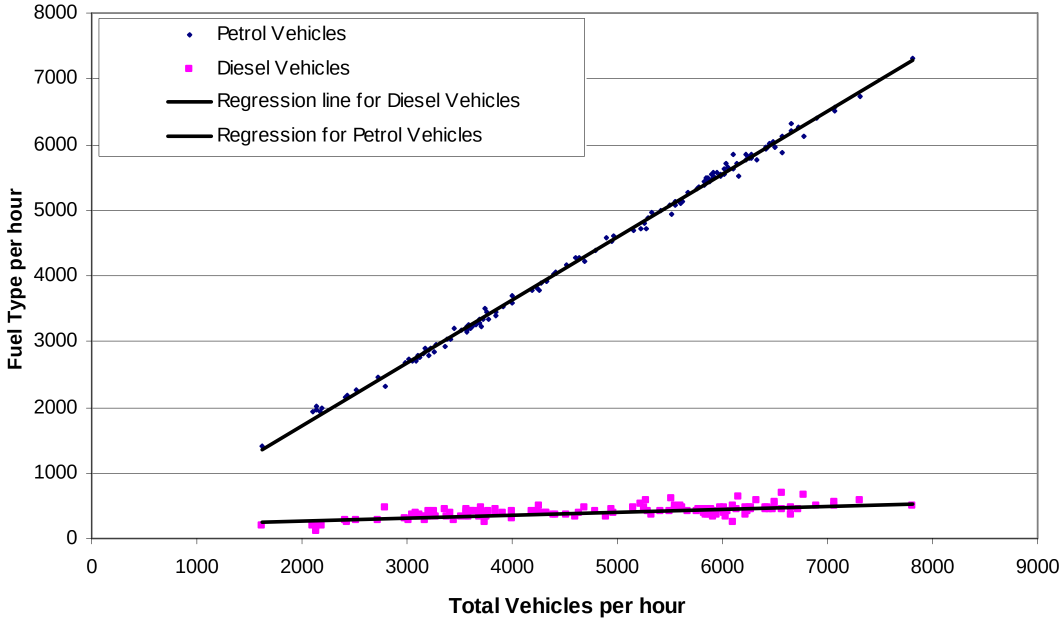

Figure 2. Observed petrol and diesel fuelled vehicles as a proportion of the total fleet

3.2 Particle Related Data

The particle counts for each five minute period have been included in the database along with the corresponding vehicle and metrological data. As the particle data is also part of a time series, this has also been smoothed by using the same moving average applied to the vehicle data and are represented graphically in Figure 3.

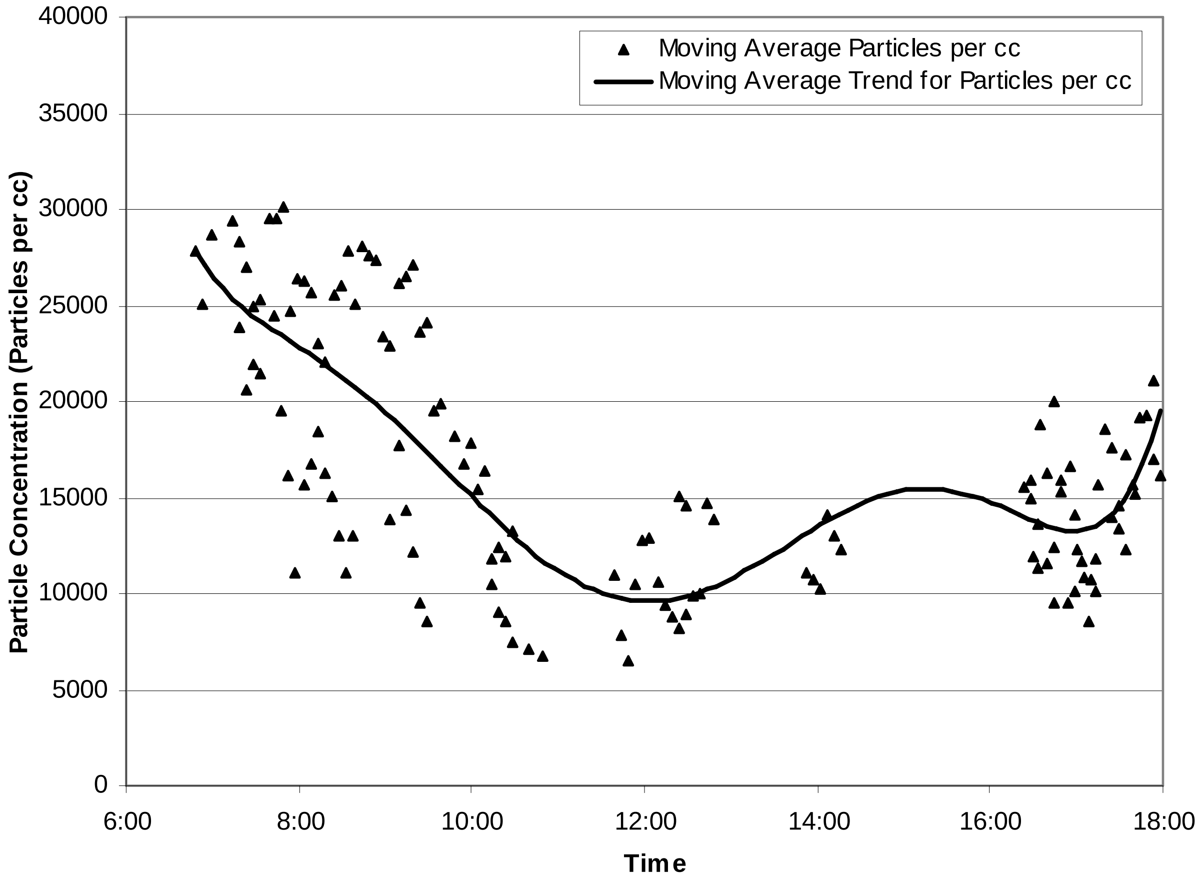

Figure 3. Observed moving average particle counts for the three-day weekday video dataset.

The r^2 values for the curves of best fit for raw particle counts and smoothed moving average particle counts are 0.42 and 0.58 respectively, indicating that there is a significant improvement to be obtained from smoothing the data. One explanation for this improvement is that the actual particle sampling process occurs dynamically over a period of 5 minutes, during which time the traffic flow is changing. Particles being collected may actually be contributed by the vehicles in the same time frame, by earlier vehicles, or may have been moved into the collection area by wind from further along the freeway. At a wind speed of 5 kph, particles can be moved 416m from their source during the five minutes sampling period. This introduces an element of uncertainty into correlating the count with a particular vehicle stream.

Wind speed is a significant variable contributing to the final concentration of particles in two situations.

Firstly, it will contribute to the actual production of particles, as a vehicle travelling into the wind experiences increased fuel consumption, which results in increased emissions over the same length of road or time period. The converse also applies. In this study with two way traffic, there will be a compensating effect on particle production, especially when there are equal traffic flows in each direction. It is assumed that this effect could be not be adequately measured or demonstrated in this data, particularly at the wind speeds of interest. A vehicle travelling at 100 kph into a head wind of 5 kph will have a true wind speed of 105 kph. As this study involves free flowing freeway traffic, the range of vehicle speeds studied range from 85 to 110 kph. The effect of a 5 kph wind speed on particle production over this range of individual vehicle speeds will be swamped by the individual vehicle speed range, and the compensation from vehicles travelling both ways.

Secondly, the wind speed has a much greater effect on the final concentration of particles by missing and removing particles from the immediate environment. This has been demonstrated by Jamriska et al (2001) in their discussion of the box model, and previously illustrated in Figure 3.

4.0 Model Development

Many sources contribute to the emission of particle. From this, it is assumed that the concentration of particles in the air is the sum of the background particles plus the net contribution from vehicle activity. This can be expressed as:

$$C_p = B_p + V_{net} \qquad \text{(Eqn 2)}$$

Where:
C_p - Measured Particle Concentration (particles per unit volume)
B_p - Background Particle Concentration (particles per unit volume)
V_{net} -Net Vehicle Contribution of Particles, expected to be the gross amount of particles produced by the vehicles into a given unit volume less those removed by dispersion mechanisms.

The major dispersion mechanism is wind, measured as wind speed. Jamriska et al (2001) have shown that the direction and speed of the ambient wind is a significant controlling factor on the total observed concentration of particles.

There are other significant variables that can impact and control the particle concentrations, such as traffic congestion, topography, rainfall, humidity, and temperature. In this study, only free flowing traffic measurements have been considered, topography remains constant, and rainfall data has been removed. Jamriska et al (2001) have also shown that temperature and humidity do not have an impact that is statistically significant, and this is corroborated by other unpublished work by the author.

An initial analysis was undertaken to investigate the relationship between the major independent variables of vehicle flow and wind speed on the observed concentrations. These results are shown in Figure 5. From this sample (n=155) it can be seen that concentration increases with an increase in vehicle flow but decreases with wind speed.

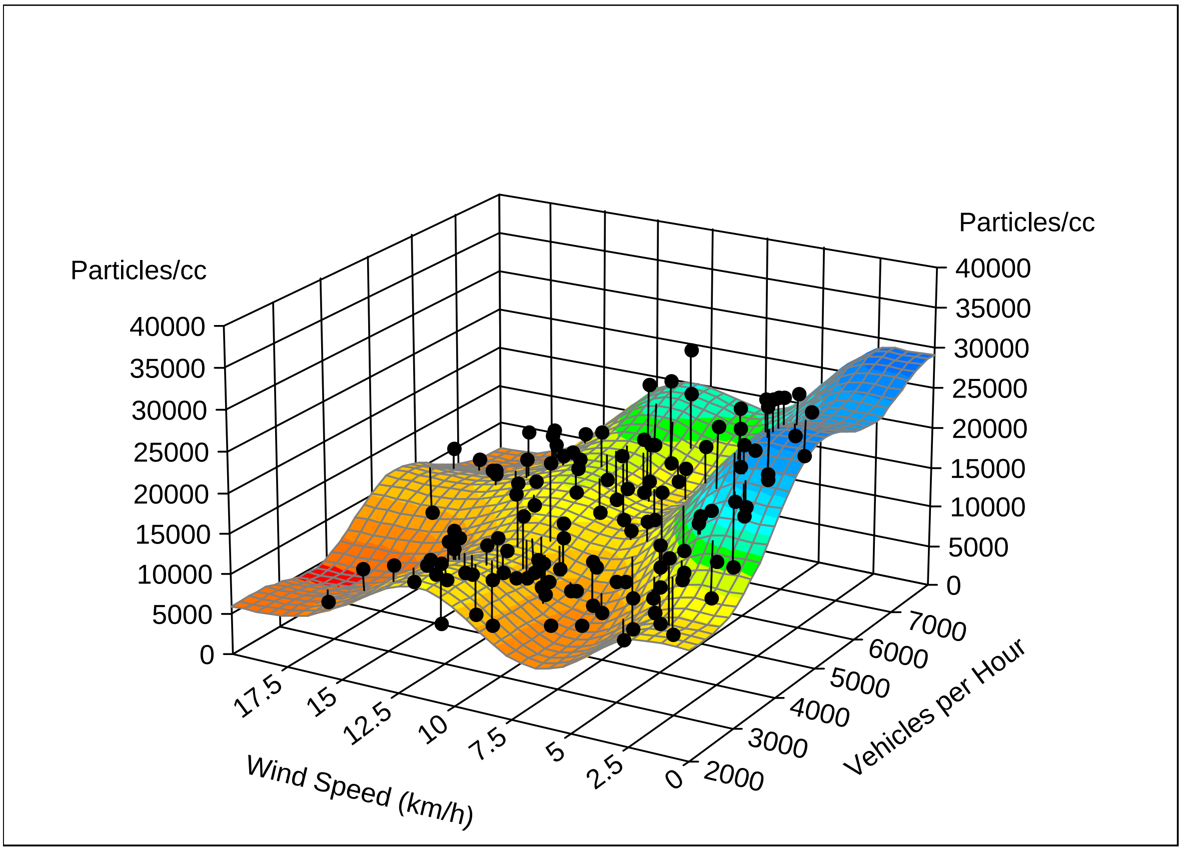

Figure 4. Particle concentrations (particles per cc) plotted against vehicle flow and wind speed for video data

As shown in Figure 4, the highest concentrations occur when the vehicle numbers are high and the wind speed is low. By keeping the wind speed as a constant, it is possible to remove one of the significant independent variables from the each examined scenario.

To test this hypothesis, analysis was done on the total database of five-minute vehicles flows recorded with associated particle counts, (8,628 data points). Weekday data only was selected and categorised into wind speed categories. Outliers were removed and analysis of the moving averages for raw vehicle flow rates against particle counts then produced a family of curves shown in Figure 6. The lowest wind speed allows the highest particle concentration and the equations to these curves are of the form $y = ax^n$. However, for the higher vehicle flows and the low wind speeds, it can be seen that the curves approximate a straight line. In this preliminary analysis, no allowance was made for the wind direction relative to the road.

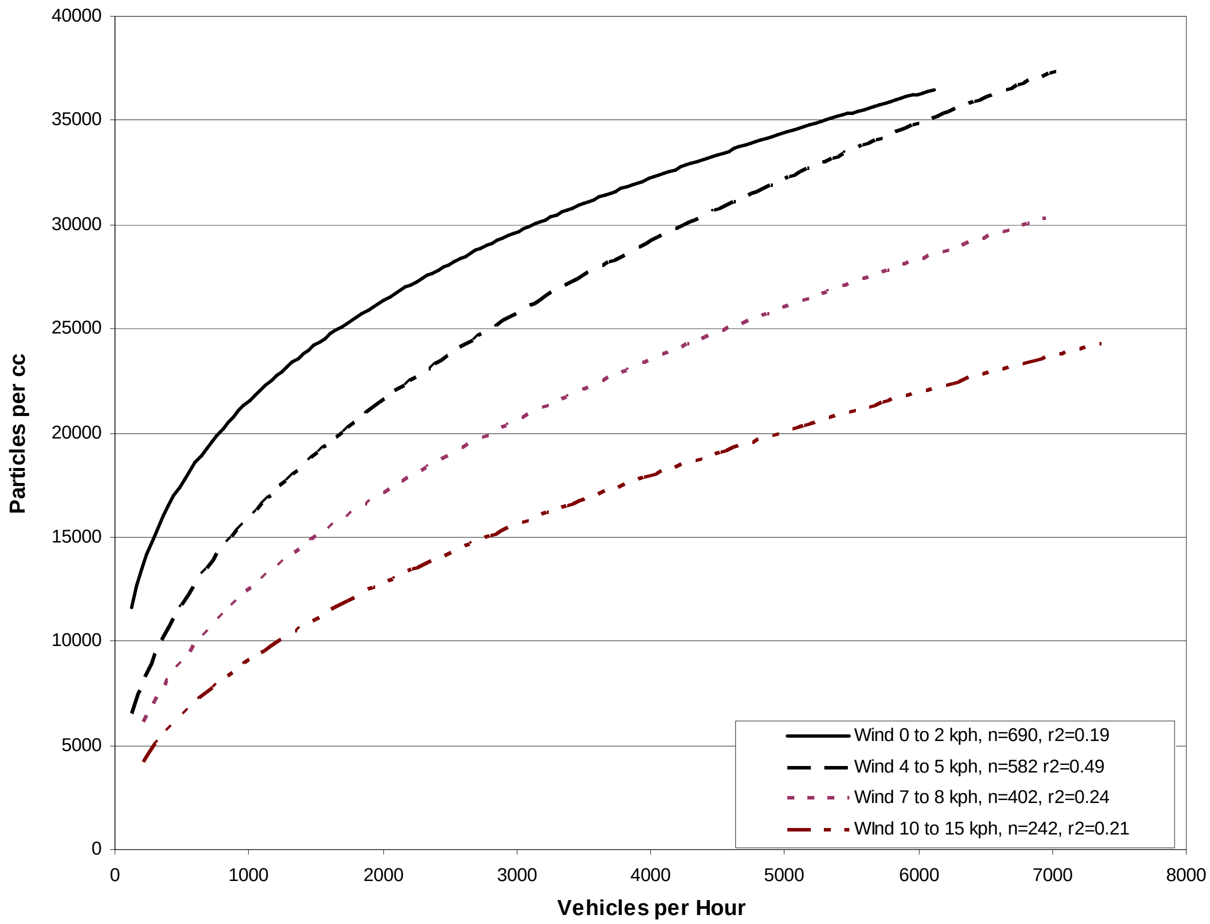

Figure 5. Vehicle flows, particle counts by wind speed. Full weekday dataset.

Additional analysis was then undertaken on the video dataset only. In order to use a statistically significant sample, the data selected was for weekdays, with wind speed less than or equal to 5 kph, for free flowing traffic. (n=47.)

A worst case scenario to produce high particle concentrations would be with high vehicle flows and low wind speed. High daytime vehicle flows produce more emissions in the same time period, and low wind speeds would not remove particles from the area quickly and allow concentrations to build up. This data (wind speeds <= 5kph) containing the fleet fuel split was analysed with multiple linear regression using the two fuel types as independent variables.

Allowing for a conservative average background particle count of 6,000 particles per cc, the following equation was obtained with an r^2 value of 0.64 and n = 47.

$$PC = -3161 + 1.75\,Pv + 42\,Dv \qquad \text{(Eqn 3)}$$
$$\quad (-1.2) \quad (2.9) \quad (6.0)$$

Where:
PC = Particle Concentration in Particles per cc
Pv = Petrol Vehicle Flow in veh/h
Dv = Diesel Vehicle Flow in veh/h
( ) "t" statistics are in parenthesis

The relative value of the coefficient for Dv and its significance indicates that the model would be quite sensitive to changes in the proportion of diesel fuels, as also found by Jamriska et al (2001). Although there are relatively few diesel vehicles on the road network they have a significant impact on the production of particles. Any increase of these vehicles would also have a significant contribution to the increase of concentration levels.

Figure 6 shows the regression equation and the actual data points used in the regression analysis. The projection of the model line gives approximately 6000 particles per cc for zero traffic flow, the concentration of background particles discussed previously. There are boundary conditions with this linear analysis, with a lower bound of 1,500 vehicles per hour, below which the formula used to calculate the proportion of diesel vehicles to the overall flow (Figure 2) becomes non-linear.

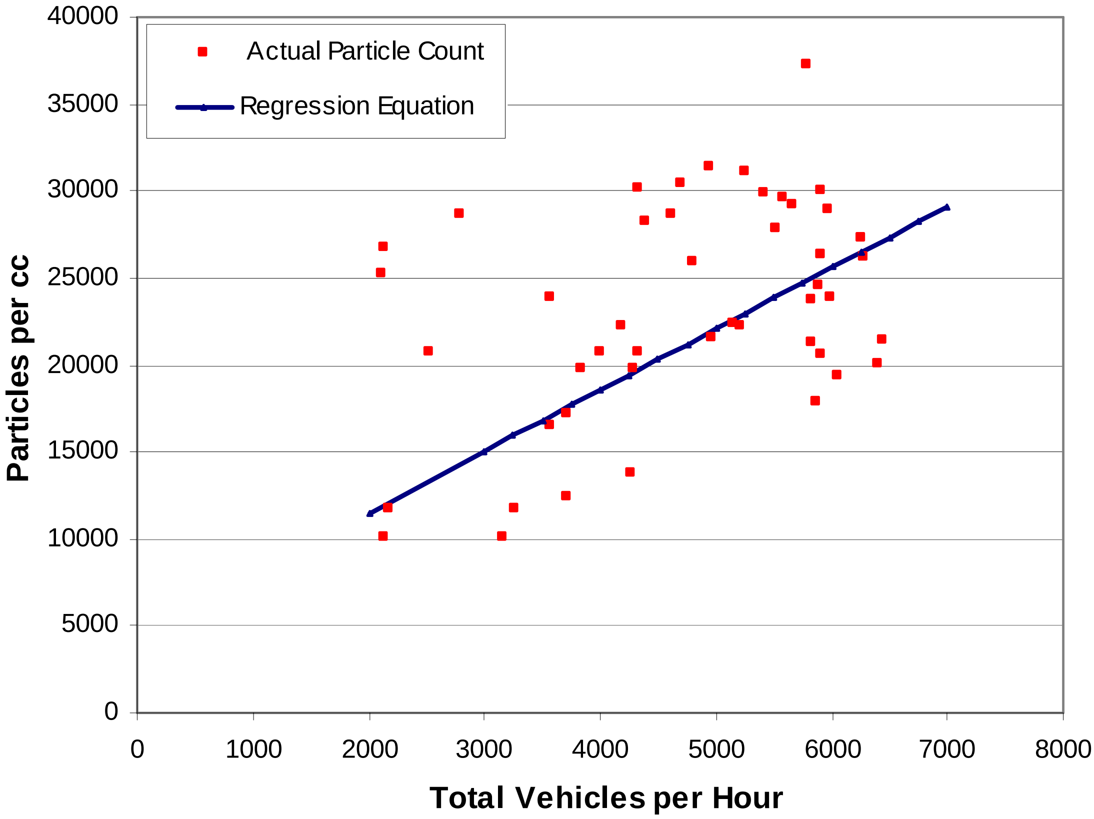

Figure 6. Observed and modelled particle concentrations for video dataset vehicle flow for wind speed less than 5 kph

Figure 7 demonstrates in percentage terms how the particle concentration increases for percentage increases in fuel types from a base of 4000 veh/h. This indicates that particle concentration is sensitive to an increase in diesel fuelled vehicles, as an increase of 20% of diesel vehicles will increase particle concentrations by 18%. This represents a numerical change from 500 to 600 diesel vehicles for a base flow of 4000 veh/h. It would require an increase of 52% in petrol vehicles numbers, from 4000 to 6080, to give an 18% increase in particle concentrations. The same numerical increase of 100 petrol vehicles represents a 3% increase in numbers and only increases the particle concentration by approximately 2%.

With increasing numbers of freight transport vehicles, it is quite possible to see an increase in diesel vehicles numbers of this magnitude. These results are significant given the likely increased demand for road based freight transport as this may lead to significantly increased levels of diesel fuelled vehicles and hence increased concentrations of particles.

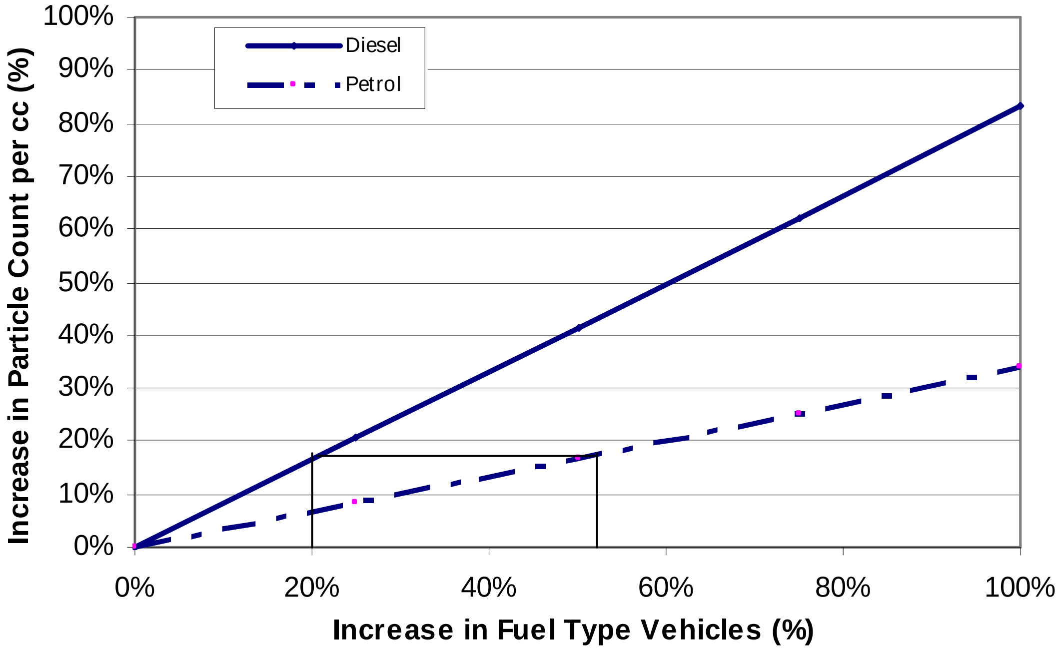

Figure 7. Effect of increase of fuel type on percentage increase of particle concentrations, for a base flow of 4,000 veh/h and wind speed <= 5kph

5.0 Conclusion

This study concentrated on a single scenario of motorway traffic on a level road running through a semi-canyon, for 6am to 6 pm weekdays. In order to simulate a worst case scenario, only low wind speeds were considered, as it was found that high traffic flows with low wind speeds produced the highest concentrations of particles.

The model process in this study shows that it is possible to achieve a satisfactory result using data that is already being collected by authorities, such as vehicle counts, vehicle fuel ratios, and wind speed data to estimate particle concentrations at a point of interest.

It has also shown that sub-micrometer particle concentrations are sensitive to increases in the ratio of diesel to petrol fuelled vehicles, with a small increase of diesel fuelled vehicles contributing to a significantly large increase in concentrations.

Such a model can then be linked with strategic models used to forecast future link demands to estimate what the concentration increase would be from increased flows.

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Table 2
Percentage Classification of Queensland Vehicles by Fuel Type (%)

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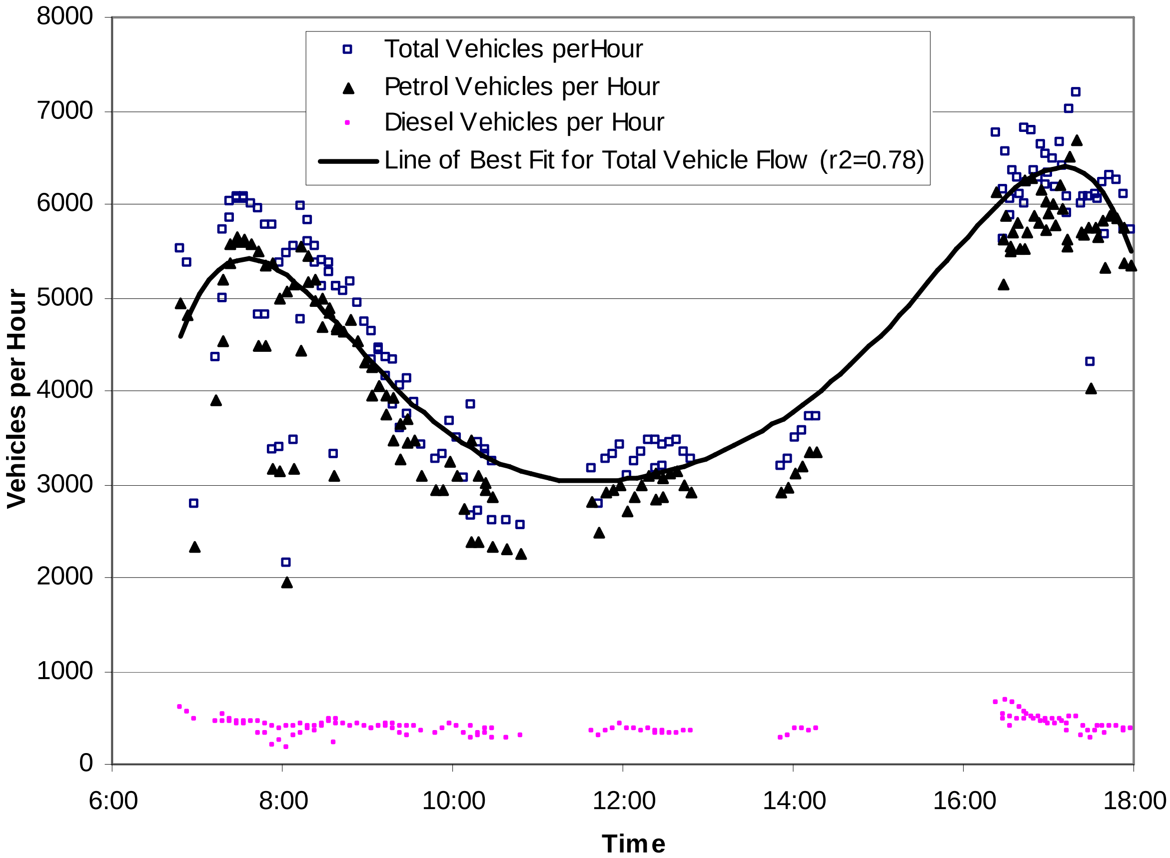
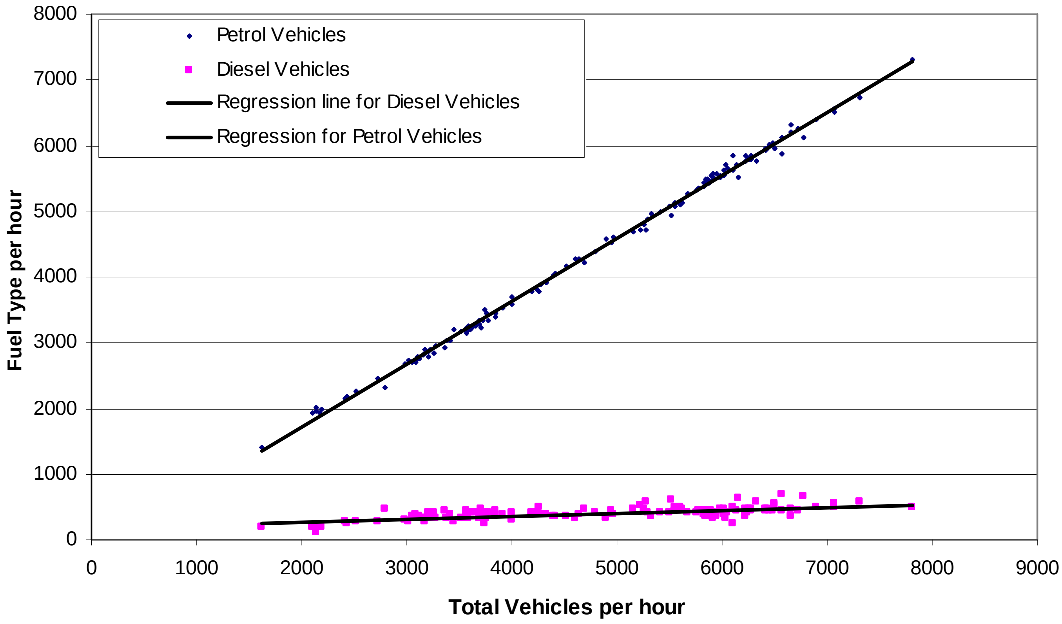
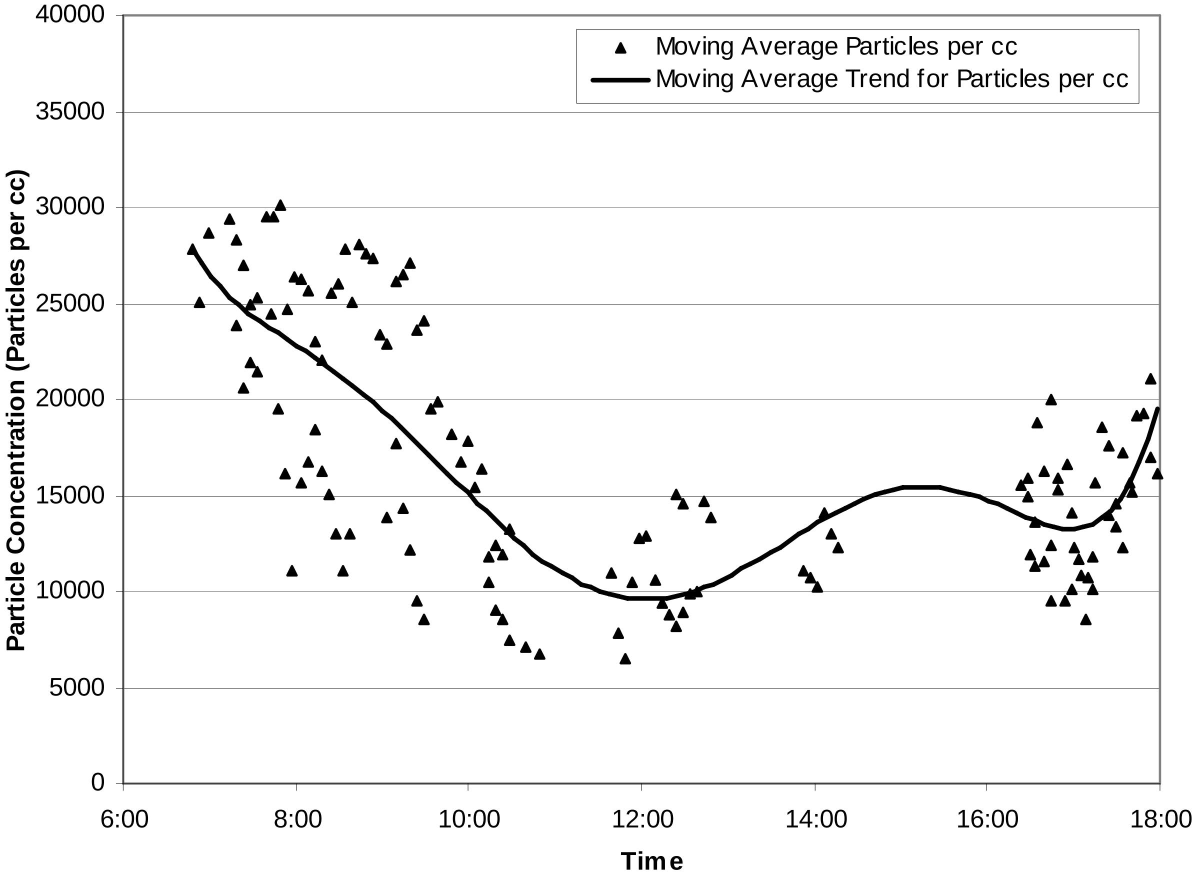


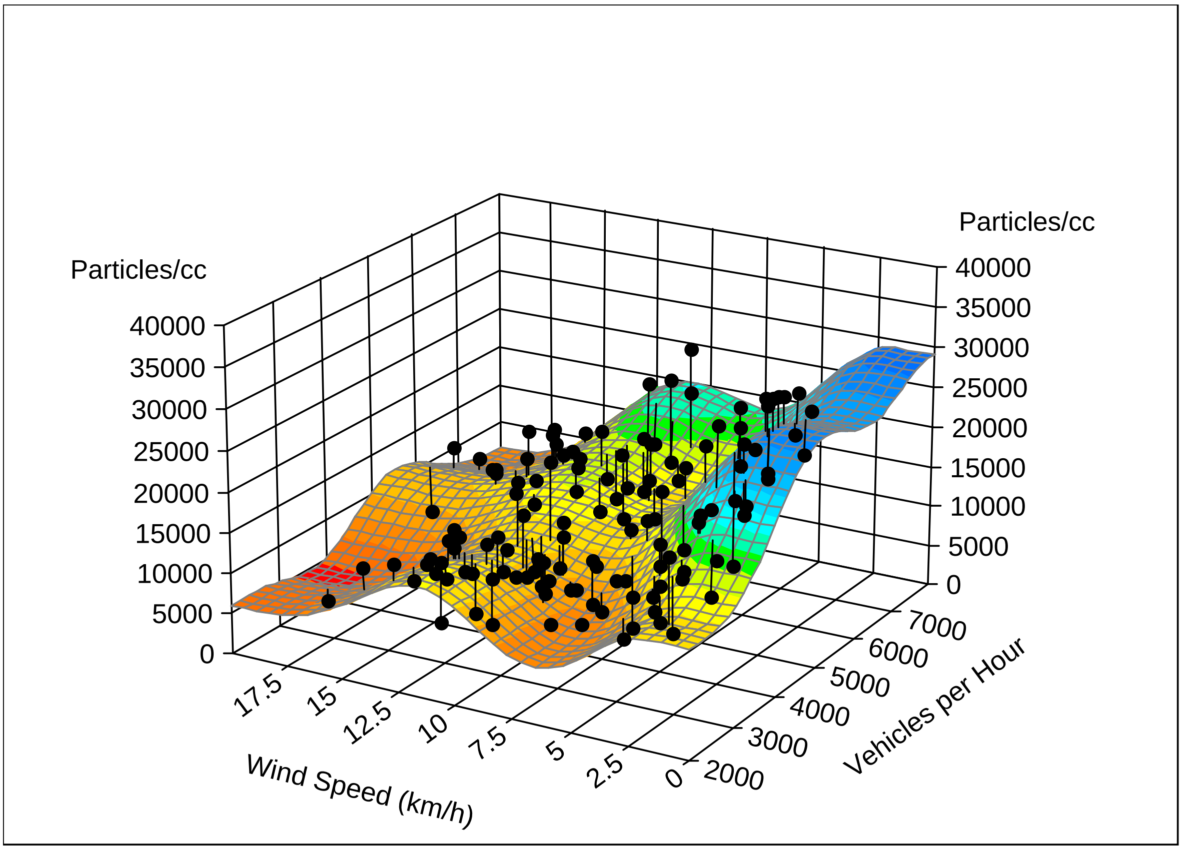
8000
7000
6000
5000
4000
3000
2000
1000
0
Vehicles per Hour
Total Vehicles perHour
Petrol Vehicles per Hour
Diesel Vehicles per Hour
Line of Best Fit for Total Vehicle Flow (r2=0.78)
6:00
8:00
10:00
12:00
14:00
16:00
18:00
Time

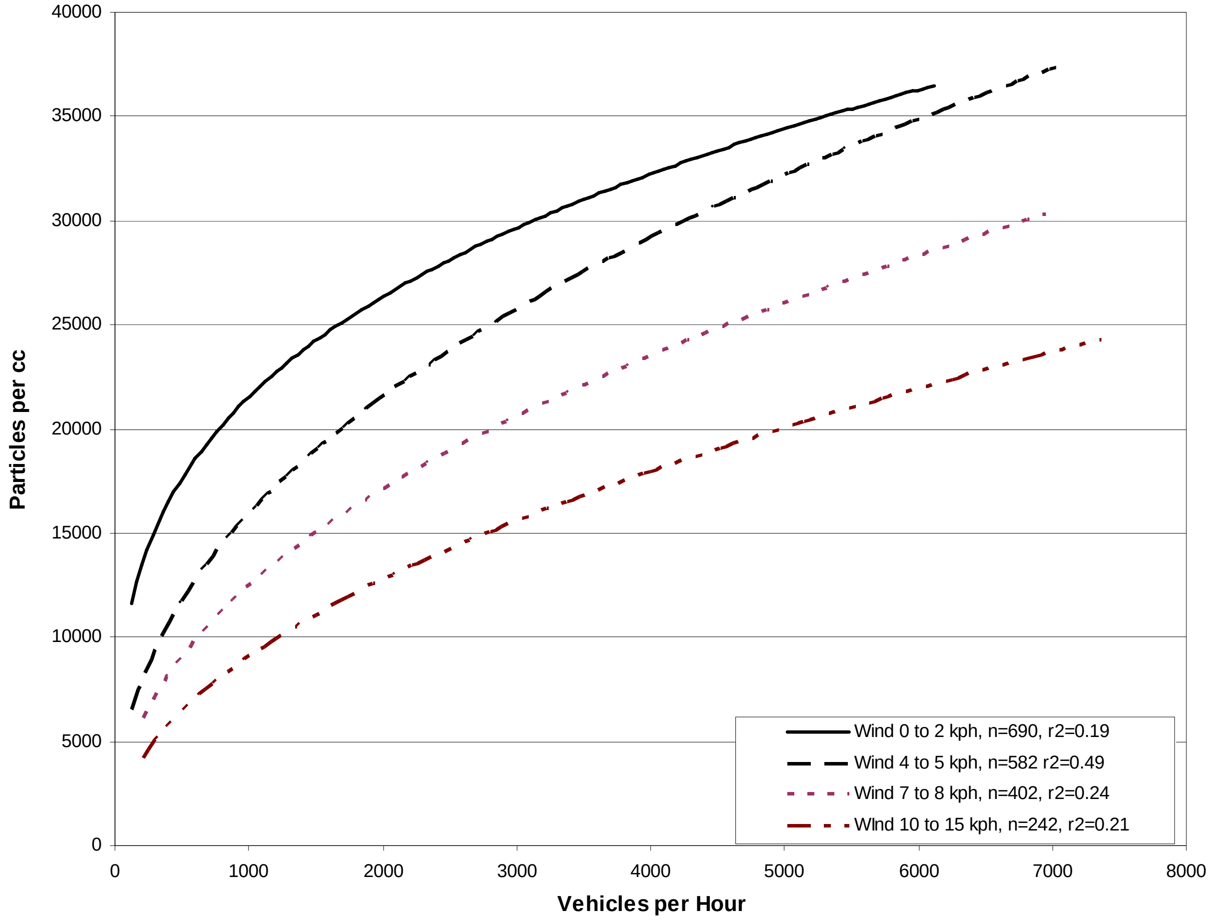


Petrol Vehicles
Diesel Vehicles
Regression line for Diesel Vehicles
Regression for Petrol Vehicles
Fuel Type per hour
Total Vehicles per hour
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

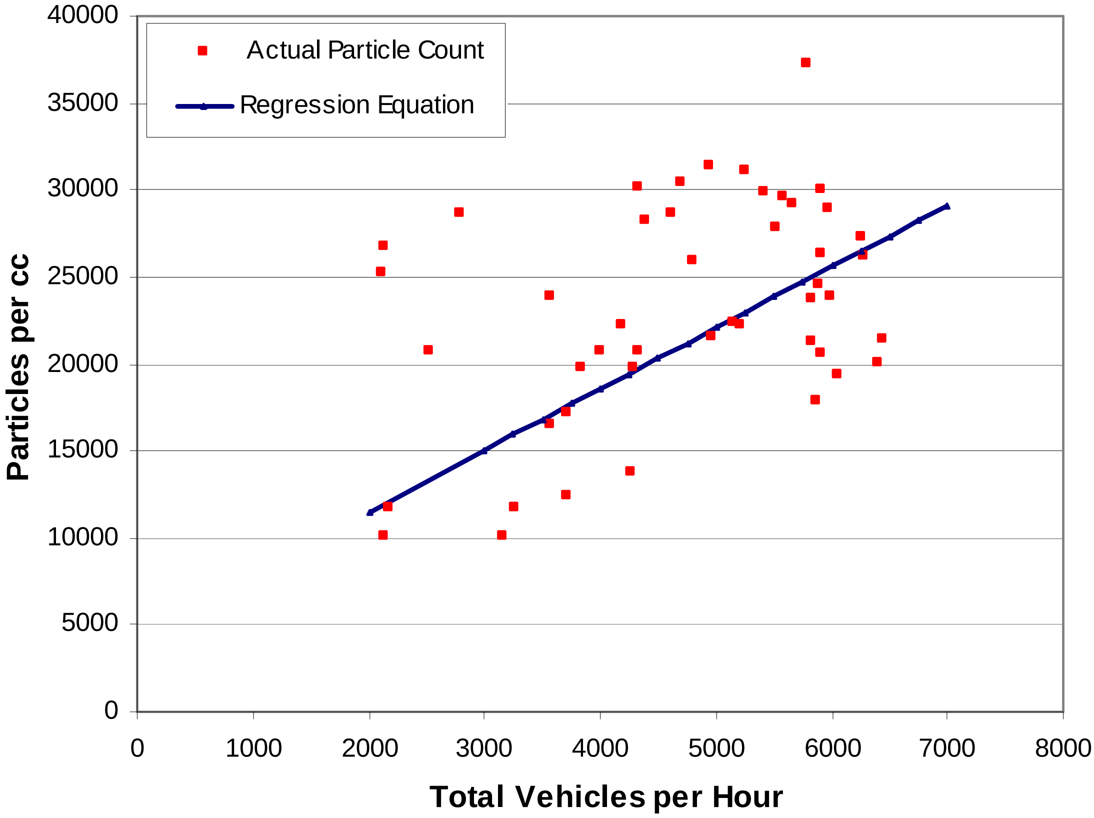


Moving Average Particles per cc
Moving Average Trend for Particles per cc
Particle Concentration (Particles per cc)
40000
35000
30000
25000
20000
15000
10000
5000
0
6:00
8:00
10:00
12:00
14:00
16:00
18:00
Time

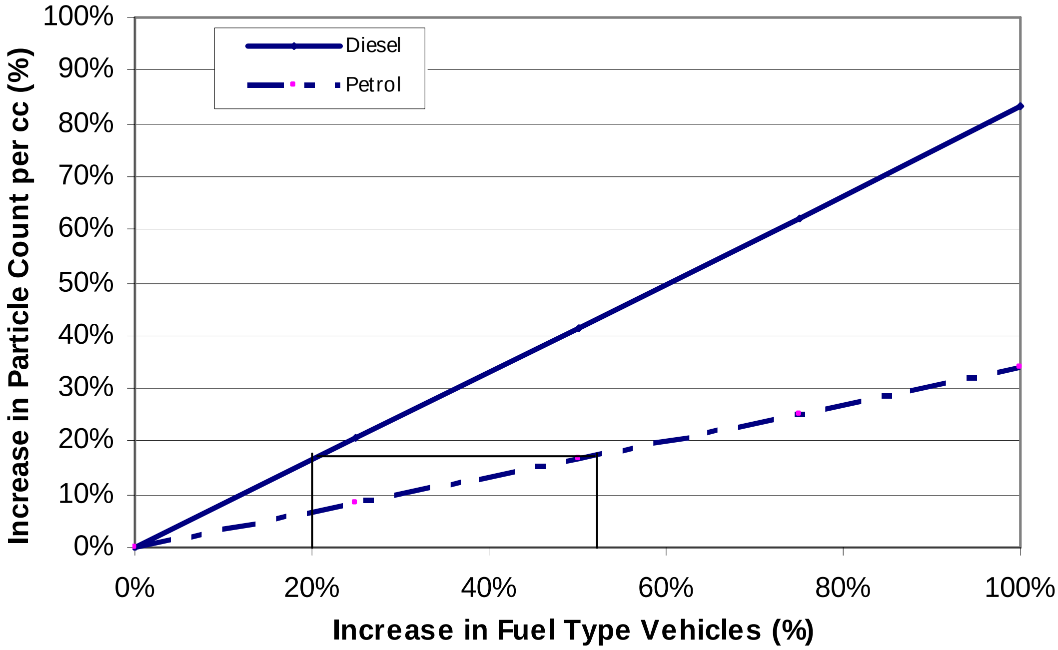

Particles/cc
40000
35000
30000
25000
20000
15000
10000
5000
0
Particles/cc
40000
35000
30000
25000
20000
15000
10000
5000
0
17.5
15
12.5
10
7.5
5
2.5
0
Wind Speed (km/h)
2000
3000
4000
5000
6000
7000
Vehicles per Hour



Particles per cc
40000
35000
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Vehicles per Hour
Wind 0 to 2 kph, n=690, r2=0.19
Wind 4 to 5 kph, n=582 r2=0.49
Wind 7 to 8 kph, n=402, r2=0.24
Wind 10 to 15 kph, n=242, r2=0.21



Actual Particle Count
Regression Equation
Particles per cc
Total Vehicles per Hour
0
5000
10000
15000
20000
25000
30000
35000
40000
0
1000
2000
3000
4000
5000
6000
7000
8000



Diesel
Petrol
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0%
20%
40%
60%
80%
100%
Increase in Particle Count per cc (%)
Increase in Fuel Type Vehicles (%)

Modelling of Sub-micrometer Particle Concentrations in Free-flowing Freeway Traffic: Some Empirical Results

Author - Fraser McGregor

Figure captions

Figure 1. Moving average weekday vehicle flow by fuel type from video data

Figure 2. Observed petrol and diesel fuelled vehicles as a proportion of the total fleet

Figure 3. Observed moving average particle counts for the three-day weekday video dataset.

Figure 4. Particle concentrations (particles per cc) plotted against vehicle flow and wind speed for video data.

Figure 5. Vehicle flows, particle counts by wind speed. Full weekday dataset.

Figure 6. Observed and modelled particle concentrations for video dataset vehicle flow for wind speed less than 5 kph

Figure 7. Effect of increase of fuel type on percentage increase of particle concentrations, for a base flow of 4,000 veh/h and wind speed <= 5kph